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Original article

The rudist buildup depositional model, reservoir architecture and development strategy of the cretaceous Sarvak formation of Southwest Iran

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A B S T R A C T

This paper studies the lithofacies, sedimentary facies, depositional models and reservoir architecture of the rudist-bearing Sar-3 zone of Cretaceous Sarvak in the Southwest of Iran by utilizing coring, thin section, XRD data of five coring wells and 3D seismic data. Research results include the following: According to lithofacies features and their association, the rudist-mound and tidal flat are the main microfacies in the Sar-3 depositional time. By investigating the regional tectonic setting and seismic interpretation, a depositional model was built for the Sar-3 zone, which highlights four key points: 1) The distribution of the rudist-buildup is controlled by the paleo-high. 2) The build-up outside of the wide colonize stage but reached the wave-base level in a short time by regression and formation uplift, and was destroyed by the high energy current, then forming the moundy allochthonous deposition after being dispersed and redeposited. 3) The tidal flat develops widely in the upper Sar-3, and the deposition thickness depends on the paleo-structure. The tidal channel develops in the valley and fringe of the Paleo-structure. 4) The exposure within the leaching effect by the meteoric water of the top of Sar-3 is the main controlling factor of the reservoir vertical architecture. The Sar-3 zone featured as the dualistic architecture consists of two regions: the lower is the rudist reef limestone reservoir and the upper is the tidal condense limestone interlayer. The thickness of each is controlled by the paleo-structure. The Paleo-high zone is the preferential development zone. Based on reservoir characteristics of the different zones, a targeted development strategy has been proposed. Keeping the trajectory in the middle of the oil-layer in the paleo-high, and in the paleo-low, make the trajectory crossing the oil-zone and then keep it in the lower.

1. Introduction

Rudists are one vital reef builder of the Cretaceous, the formed reef and related reservoir play as an important role in the world [17,18,24]. Particularly in the Middle East, the rudist bearing reservoir always contains huge reserves [18,28]. However, the formation with rudist fossil found in China [11,23] has so far been found without any related oil/gas reservoir. Accordingly, the knowledge about the depositional model, reservoir characteristics and exploration experience with rudist bearing

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carbonate reservoirs has been extremely limited for Chinese scholars. Recently, with the increasing foreign cooperative projects related to rudist reservoirs by Chinese oil companies [8,16], it is very important and valuable to study it.

The Middle East scholars have built the rudist depositional model by considering different influencing factors including paleoclimate, sea-level fluctuation, tectonic activity, etc. [7,19,28,5,26,13, 20–22]. Although there have been achievements in various aspects, but all of them focused on the rudist reef itself which represents the good reservoir. In the oil fields along the Iran–Iraq border zone, it was believed that the distribution of rudist buildup was controlled by the paleo-high [20–22,28]. The paleo-topography of the field area could cause different lithofacies, depositional characteristics and digenetic environment as well as further impact on the reservoir architecture. This paper considers the rudist bearing zone of the Cretaceous Cenomanian Sarvak in the SA oil field in southwest of Iran as a research object, mainly to study the rudist buildup depositional model and the corresponding reservoir architecture, then propose a future development strategy for the oil field.

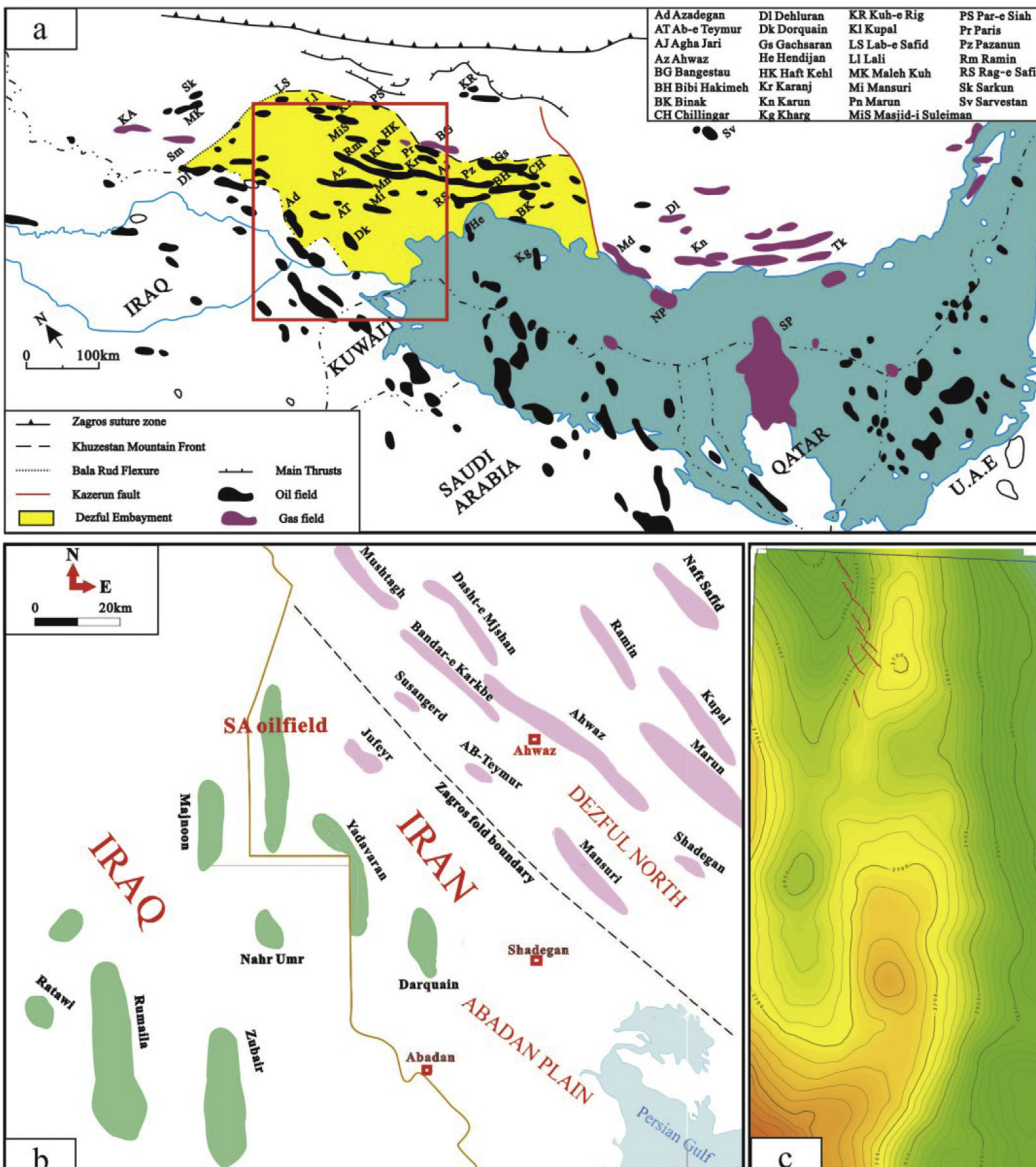

Fig. 1. Location map of oil and gas fields in the Zagros Foothills and Persian (Arabian) Gulf: (a) The geographic location map of the SA oil field in the Dzeful embayment; (b) The structural map of the Sarvak Formation of the SA field; c).

2. Materials and methods

The database that includes in excess of 500 samples from 6 coring wells in the field, and the corresponding core description, digital photographic images and thin section petrographic analysis were used to study the lithofacies including lithology, grain size, grain and fossil types. The classification of lithofacies followed the nomenclature of Dumham (1962) [9]; and was subdivided by bio-fossil type and sedimentary texture. The 3D seismic data covering an entire area of 971 km^2 in the field was used to interpret the special sedimentary characteristics such as tidal channel, and reconstruct the paleo-structure which represents the depositional environment of the field by using the horizon flattening technique. The entire conventional suite of logging data on 26 wells was fully interpreted and used to correlate the strata and reservoir.

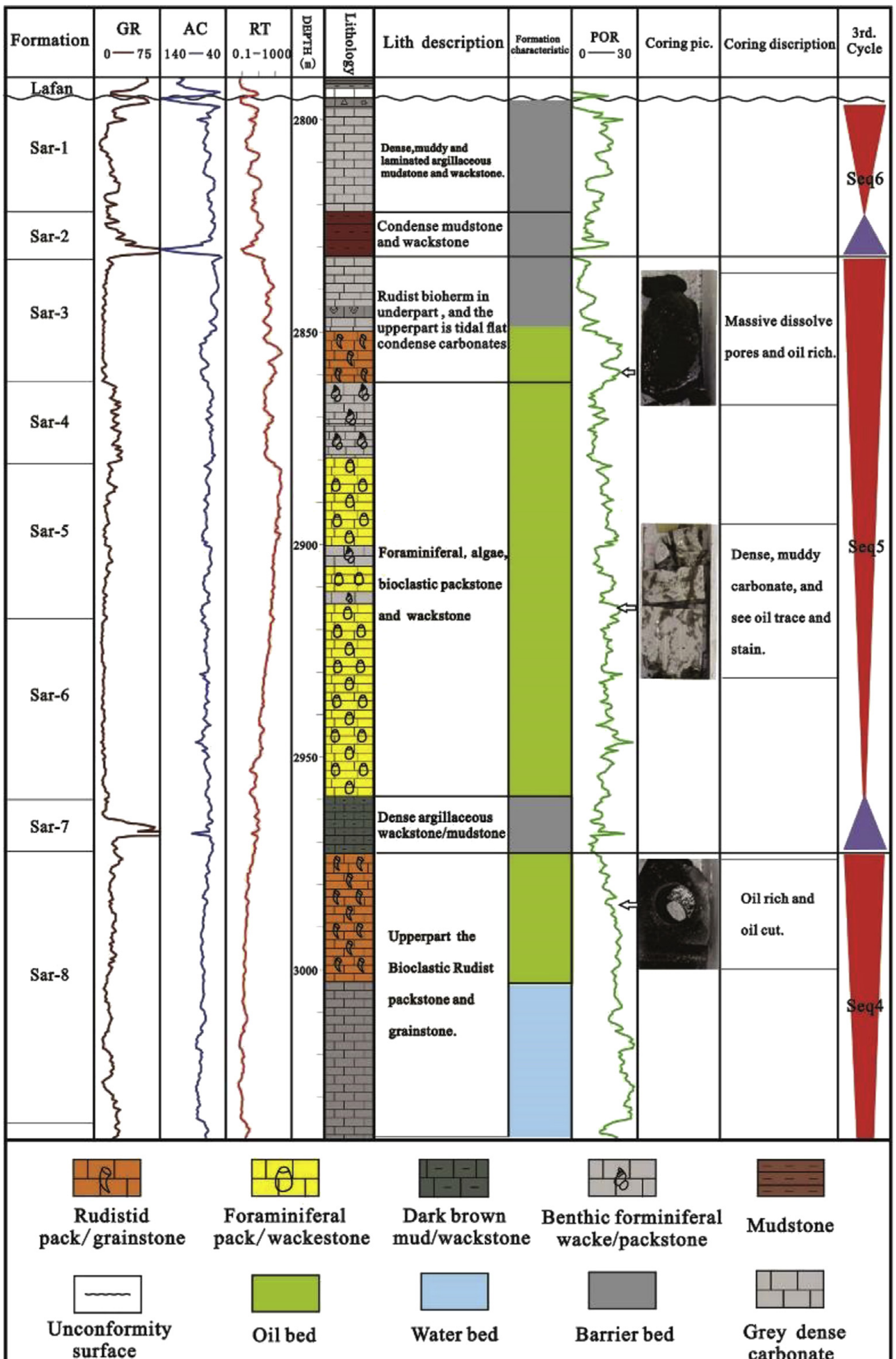

Fig. 2. The schematic stratigraphy histogram of the upper Sarvak Formation of the SA oil field, Iran.

3. Geological setting and development situation

The tectonic setting of the SA oil field is situated in the transition zone between the Zagros basin foreland and Arabia platform, west of the Dezful embayment, and geographically located in the southwestern Khuzestan province of Iran and the Iran–Iraq border zone. It is presently an untapped oil field within the largest reserve of the world (Fig. 1-a). Unlike other fields with the NE–SE trending in the Dezful area, it is understood that the SA oil field is a huge long-axis anticline that belongs to the N–S trend group [4,27,29], known as the Arabian Trend (Fig. 1-b), and with two crests along its length of which the southern elevation is higher than the northern (Fig. 1-c).

The Sarvak formation is interpreted to have been deposited in a shallow marine environment during the Albian to Turonian period. The presence of conglomerates, breccia and collapse feature of the upper part indicates the disconformities by the regional uplift during the late Cenomanian to Turonian period. The lower boundary with the Kazhidumi is conformable and gradational [3,28,4]. In the SA field, the Sarvak has been divided into six third cycles, and further subdivided into 12 development subzones by logging and paleontology characteristics. The oil zones of Sar-3, 4, 5, 6 and 8 are mainly in SEQ-4 and SEQ-5. Sar-1, 2 and 7 are the stable dense interlayers. Mostly, the subzones below Sar-8 are the water and dry zones. The pre-evaluation work showed that the lithology of the upper Sar-3 was tight micrite/wackstone, and the lower part is the rudist bearing grain/packstone with good oiliness and property. Sar-4, 5 and 6 zones are the foraminifer and plankton pack/wackstone of high heterogeneity, weak oiliness and property (Fig. 2).

Under the case of stable distribution, weak heterogeneity, good property and oiliness, the Sar-3 zone has been exploited by horizontal well. However, in the development phase, it also showed a strong heterogeneity mainly characterized as: 1) The thickness of reservoir presents the strong variance of different wells, and unclear the controlling factor and favorable development zone; 2) The upper tight limestone has also the same situation as the reservoir while the abnormal thickness occurred in some wells; 3) The boundary of the lower Sar-3 is not clear in the partial region causing “target zone crossing” difficulties. These problems are challenging with respect to trajectory design, tracking and drilling adjustment of horizontal wells for ensuring maximum reservoir drilling ratio and well production.

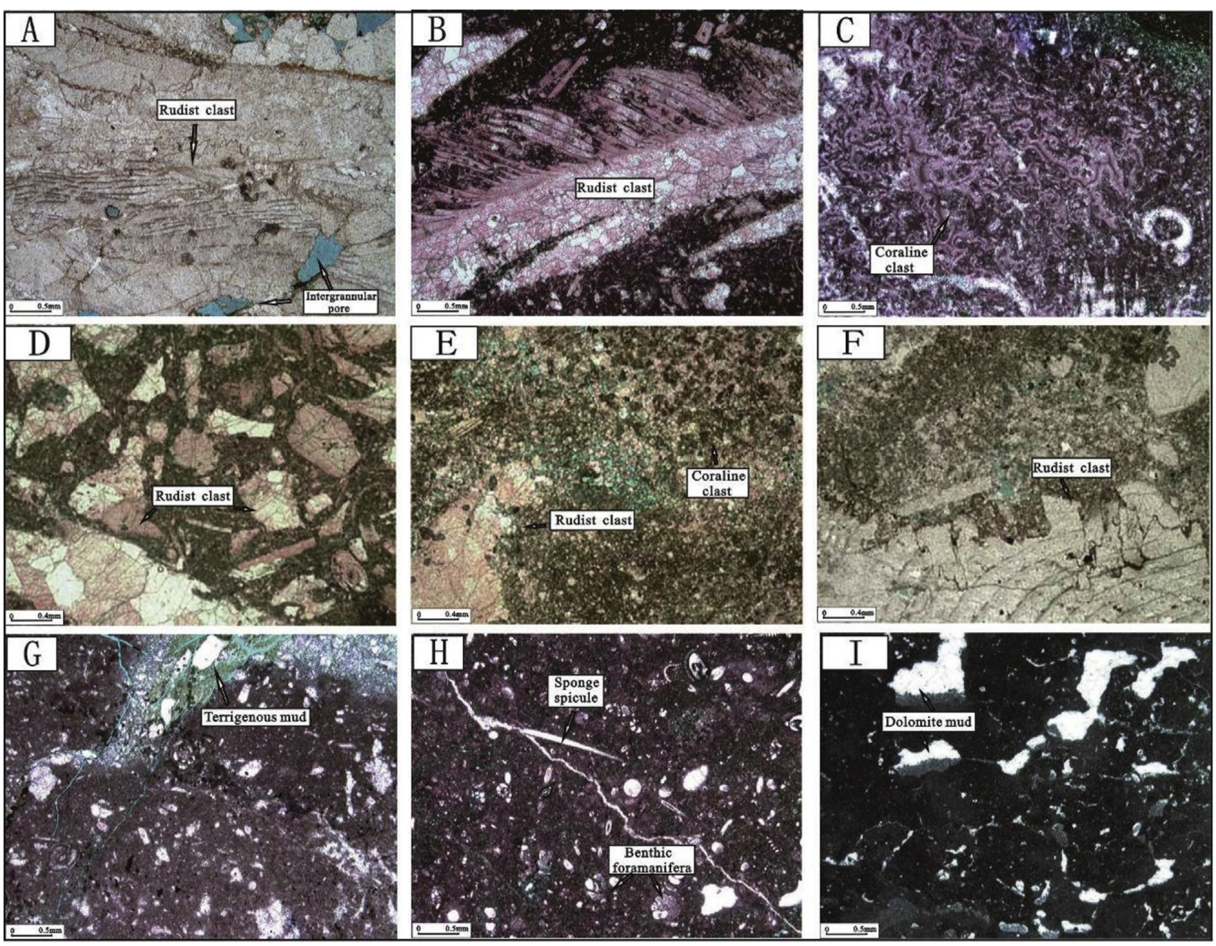

Fig. 3. Lithofacies of thin section pictures of the Sar-3 zone A) Rudist grainstone with residual (primary) intergranular macroporosity; B) Bioclastic packstone/wackestone containingrudist fragments. The large rudist fragment in the picture was originally bimineralic, consisting of calcite (upper part, microstructure well preserved) and aragonite (lower part, now blocky calcite spa). C) Peloidal/bioclastic wackestone/packstone containing the coral clast; D) The sample is a relict bioclastic packstone. Relict grains include bivalves, rudists and possible gastropods, however, most are indeterminate fragments. E) Coral pack/grainstone, the sample is a peloidal and bioclastic packstone/grainstone. Bioclasts include indeterminate rudists, radiolitid rudists and indeterminate bioclastic debris. F) The sample is a rudist dominated, bioclastic packstone. Other bioclasts include bivalves and echinoderms. Mudlined stylolitic contacts indicate some compaction. G) Bioclastic mudstone/wackestone, Terrigenous mud is present. H) Bioclastic mudstone/wackestone. Skeletal grains present include sponge spicules and benthonic foraminifera. Some sections through sponge spicules display an axial canal. A calcite vein runs across the field of view from top left to bottom right. I) Fenestral mudstone. Geopetal lime mud is present in the lower portions of fenestrae; it is overlain by calcite cement.

Chart 1
Lithofacies characteristic and deposition environment of the Sar-3 zone.

Lithofacies	Description	Depositional Environment
Radiolitid rudist pack/grainstones (Fig. 3-A, B, D, F)	Generally massive, indistinctly bioturbated, commonly bimodal, radiolitid rudist (locally intact and in situ) grainstones andpackstones/grainstones with common to abundant peloids and small benthonic foraminifera. Skeletal debris, echinoderm fragments, gastropods, Orbitolina and solitary coral debris are locally present.	Deposited in a very shallow, high energy barrier to back barrier setting.
Caprinid rudist pack/grainstones	Bioturbated (inclined and horizontal traces) caprinid rudist grainstones and packstones/grainstones with abundant peloids and alveolinid foraminifera. Intraclasts are locally present.	Deposited in a very shallow, high energy barrier setting, or locally on palaeohighs within the intrashelf.
Coralline pack/grainstones(Fig. 3-C, E)	Massive, locally bioturbated (grain-filled horizontal to subvertical traces) solitary coral grainstone and pack/grainstone with abundant peloids, bioclastic debris and local rudist debris.	Very shallow water, barrier to fore reef sediments deposited around FWWB.
Mudstones with desiccation features and rootlets (Fig. 3-G)	Mudstones and wackestones with strong evidence of exposure including: in situ brecciation and intraclast/nodule formation and terrigenous clay infiltration through strong vertical burrowing. The background mudstone sediments are dominated by peloids, blackened grains (benthonic foraminifera), bioclastic debris with bioturbation mottling and local indistinct, internodular lamination.	Inter- to supratidal zone of the tidal flat, with exposure occurring in this setting.
Burrowed mudstones with firm/hard grounds (Fig. 3-H)	Bioclastic, skeletal mudstone/wackestone with common firm grounds and hard grounds. The sediments are typically bioturbated (Horizontal to vertical) or bored, locally nodular and infiltrated clays may be present.	Formed during periods of slow deposition or hiatus in relatively sheltered areas of the intrashelf to tidal flat setting.
Fenestral mudstones (Fig. 3-I)	Benthonic foraminiferal, coated grain and gastropod mudstones with well developed, cemented fenestrae.	An intertidal setting is indicated by the fenestrae and restricted grain assemblage, in particular the algaelly coated grains.

4. Lithofacies

The coring and thin section indicates that the lithology of the Sarvak formation is dominated by limestone within the abundance of the bio-fossils including the *Rudist, Coral, benthic foraminifera (Alveolinid, Miliolid, Orbitolina), Gastropod and Algal*, as well as a very few dolomites and terrigenous siliciclastic. Relate to the Sar-3 zone, the lithofacies of the lower part are Radiolitid rudist grain/packstones, and a few of Caprinid rudist pack/grainstones and Coralline grainstones of the high energy deposit; the upper are mainly Exposed/rootletted packstones, Mudstones with desiccation features and rootlets, Fenestral wacke/mudstones, and Burrowed mudstones with firm/hard grounds of the low energy deposit (Fig. 3). Chart 1 shows the detail descriptions.

The reef builder of the field such as the *Radiolitid rudist, Caprinid rudist and Coral* is dominated by bioclast but without bondstone and bafflestone within the intact biological fossils, which indicated that the reef has been destroyed before into the wide colonize. On the contrary, in some other fields in the Middle East [28,26,5], the rudist bearing reservoirs are mainly bafflestone and bondstone like the Shuaiba formation of 100–150 m thickness in the UAE, which is totally different from the SA oil field.

5. Depositional model

5.1. Tectonic background

The overall depositional system of the Arab plate in the Cenomanian Cretaceous is likely to have been shelf (or ramp) like, and is situated in the equator area with humid weather and abundant rainfall [2,14,15,20,21]. In the field area, a regionally extensive and fluctuating shallow epeiric sea of 5–30 m was believed to be present, with a relatively distant paleo-coastline postulated to the south of the field (south of Kuwait), and the major shelf-slope break at a considerable distance to the northeast of Iran [3,10]; (Fig. 4).

The Alps tectonic activity of the late Cretaceous makes the Arab plate into the active extrusion tectonic background, and causing the reactivation of the Cambrian Najid fault and deep salt formation (Hormuz salt) uplift, thus resulting in forming the paleo-high in the Iran–Iraq border zone [19,4,26,20,21]. The paleo-high formation commenced in the late Cretaceous and across the entire Sarvak depositional stage [19,4,20–22,1]. As the in situ-karst breccia collapsed, meteoric water leaching and karsitification can be seen in the coring and thin section of the Sar-3 zone (Fig. 5). The clay minerals of Sar-2 are only commonly present in the emergent lithofacies where detrital clays, predominantly kaolinite, are infiltrated during sub-aerial exposures. Thus, the generation of local subaerial exposures can be assured

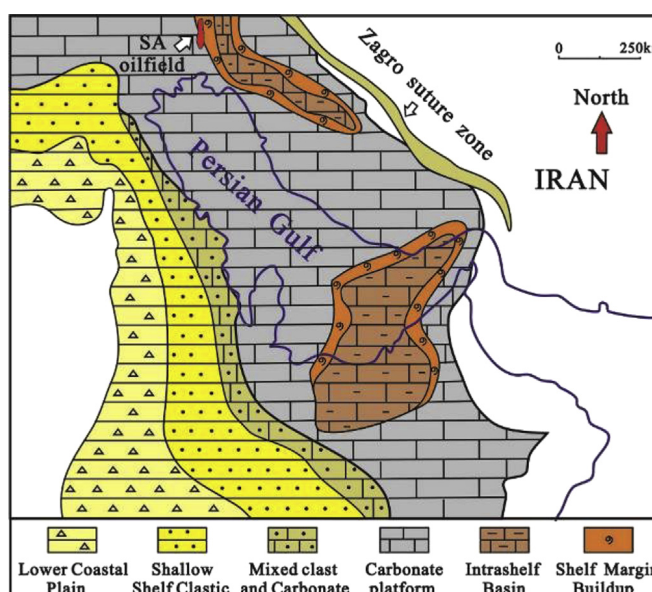

Fig. 4. The Paleogeographic map of the Middle East area during the Cenomanian–Turonian period of Upper Cretaceous (modified from Alsharhan and Nairn 1988 [2]).

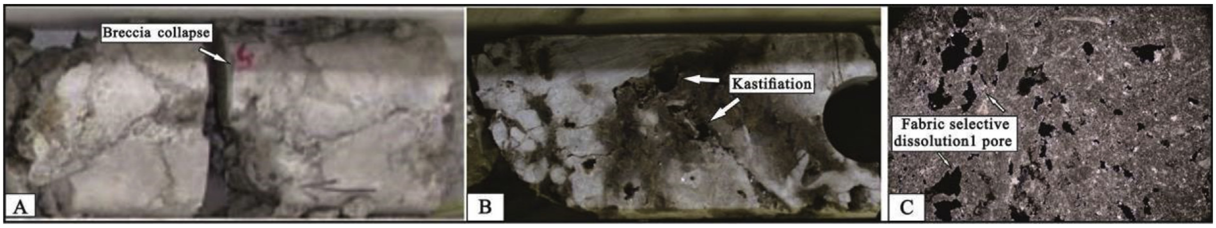

Fig. 5. The coring and thin section figures show the sub-aerial exposures occurred in the Sar-3 zone of the SA oilfield. A) Sar-3 zone coring picture: In situ-karst breccia collapse indicate the local exposure, paleo-soil filling can be seen in partly place. B) Sar-3 zone coring picture: Karstification of meteoric leaching, C) Sar-3 zone thin section: The fabric selective dissolution pore by leaching in the syngenetic period.

by the response to local topographic variations, periods of relative sea-level fall and localized paleo-highs through tectonic movement. The same phenomenon was also detected in neighboring fields in Iran and Iraq [20–22,4,12].

The channel of the NE to SW trend was interpreted in the Sarvak formation and normally distributed in the peripheral area of the paleo-high (Fig. 6-a). It shows a medium-strong amplitude and succession sag feature in the seismic section. Possibly the channel development is constrained by the paleo-high forming and without the periodicity swing characteristic compared with the normal (Fig. 6-b). The strongest sapping shown in the Sar-3 zone indicates that the water energy reaches the strongest within the sea level fall at the end of SEQ-5. The lithofacies of the upper Sar-3 in the coring well which situated in the channel zone was the grey tight limestone channel fill deposit with tabular trough cross-stratification also proving the existence of the channel (Fig. 6-c).

5.2. Sedimentary facies

According to the barrier system ramp depositional model of Tucker (1990) [25]; SEQ-5 of the Sarvak formation can be ascribed as belonging to the barrier island-shoal sub-facies by grouping lithofacies and tectonic setting (Fig. 7-A). Dividing it into four microfacies are rudist mound, associated tidal flat, shoal and lower stand shoal (Fig. 7-B). The tidal flat setting generally occurred landward of and within a more tidal influence than the platform interior. However, tidal flat environments could also have developed around isolated intrashelf highs and along the lea side of shallow, intertidal highs that developed around shallow rudist build-ups [25]; Alsharhan 1998 [10]; [13]. In this paper, it is referred to as the associate tidal flat of microfacies and brought it into the barrier island – shoal subfacies. The depositional stage of Sar-3 was the shallowest sea level and developed the associated tidal flat and rudist mound.

5.2.1. Associated tidal flat

The lithofacies of the tidal flat setting are generally dominated by low energy micrite and wackestones with locally very distinct features and minor bioclast under the warm humidity and good water circulation, and the channel developed by the topographic feature. The typical texture included rootlets, fenestrae, algal laminae and oncoids, and the logging character are high grammar, low acoustic impedance, low neutron, high density and low porosity (Fig. 8).

5.2.2. Rudist mound

The rudist mound is the highest energy within the shallow marine setting of the section studied with the wave process and dominating to some extent. The mound and relevant lithofacies identified in the section were probably a series of detached islands/shallows, forming “barrier” systems which locally or

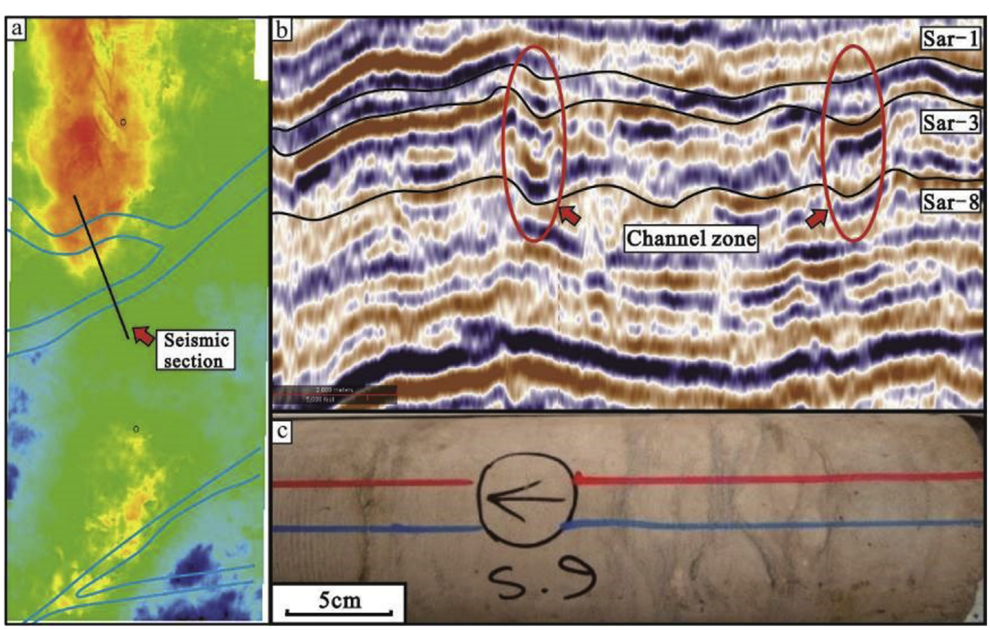

Fig. 6. The channel distribution figure of the paleotopography of the Sarvak in Palaeocene (a) The seismic section shows the channel character in the Sarvak formation. (b) The coring picture of the well in the channel zone. (c) .

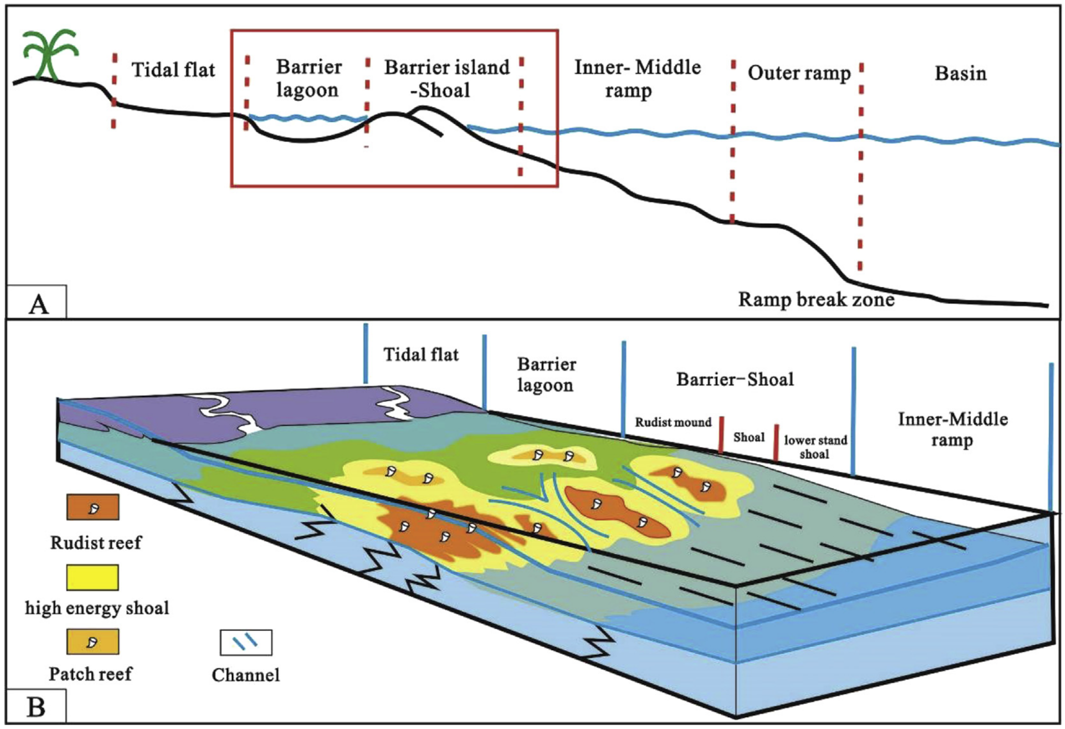

Fig. 7. The classic carbonate ramp depositonal model within barrier islands (A)Regional sedimentary model of Sar-3 depositional time (B).

regionally separate the platform environment into an open and more restricted setting. The barrier system was dominated by radiolitid rudists and locally associated with solitary corals or Caprinid rudists. The lithofacies identified within this environment are dominated by radiolitid rudist grain/pack/wackestones. The content of the grain and mud was controlled by the water energy. Close to the reef crest, the grainstone's occurrence frequency is higher, and conversely the muddy is higher. The logging characteristics are low grammar, high acoustic impedance, high neutron, low density and high porosity (Fig. 8).

5.3. Depositional model

The depositional model of Sar-3 was built based on paleogeography, paleontology, lithofacies grouping, tectonic evolution and depositional characteristics, and that is a barrier system where locally developed rudist build-ups on the barrier of the shallow water within the sufficient nutrient and sunshine provided by the formation uplift of the Alps tectonic activity (Fig. 9-A). Regionally, the rudist build-ups formed like island chain on the shallow sea and reflected the carbonate platform evolution

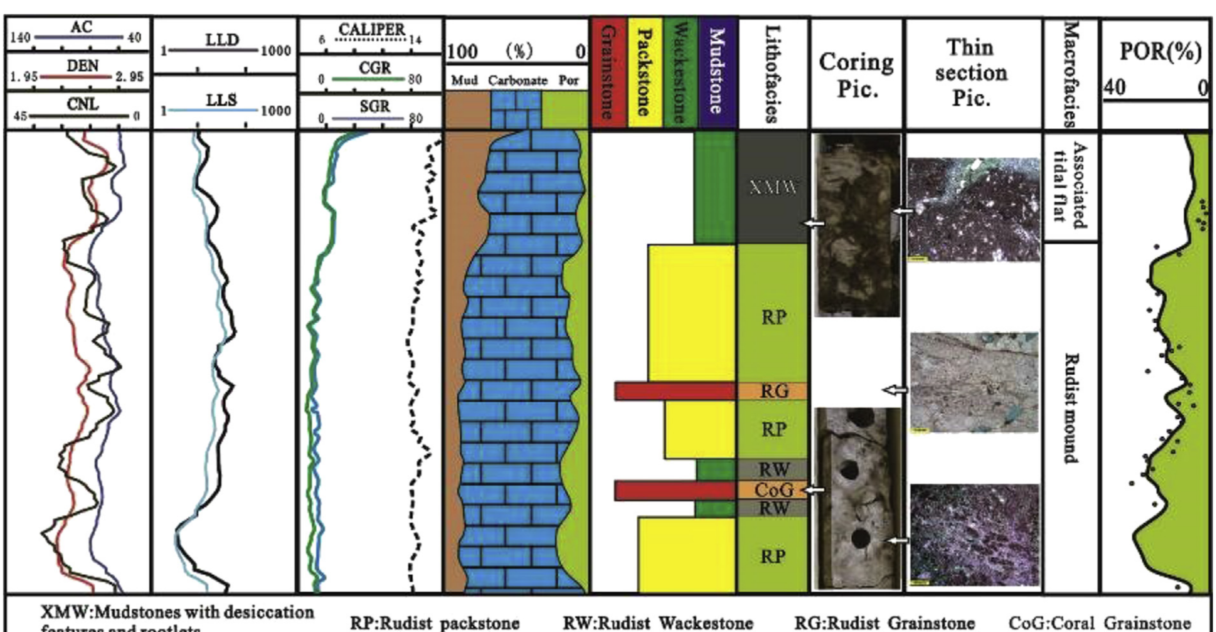

Fig. 8. Sedimentary microfacies section and logging response of the Sar-3 zone in the SA oil field.

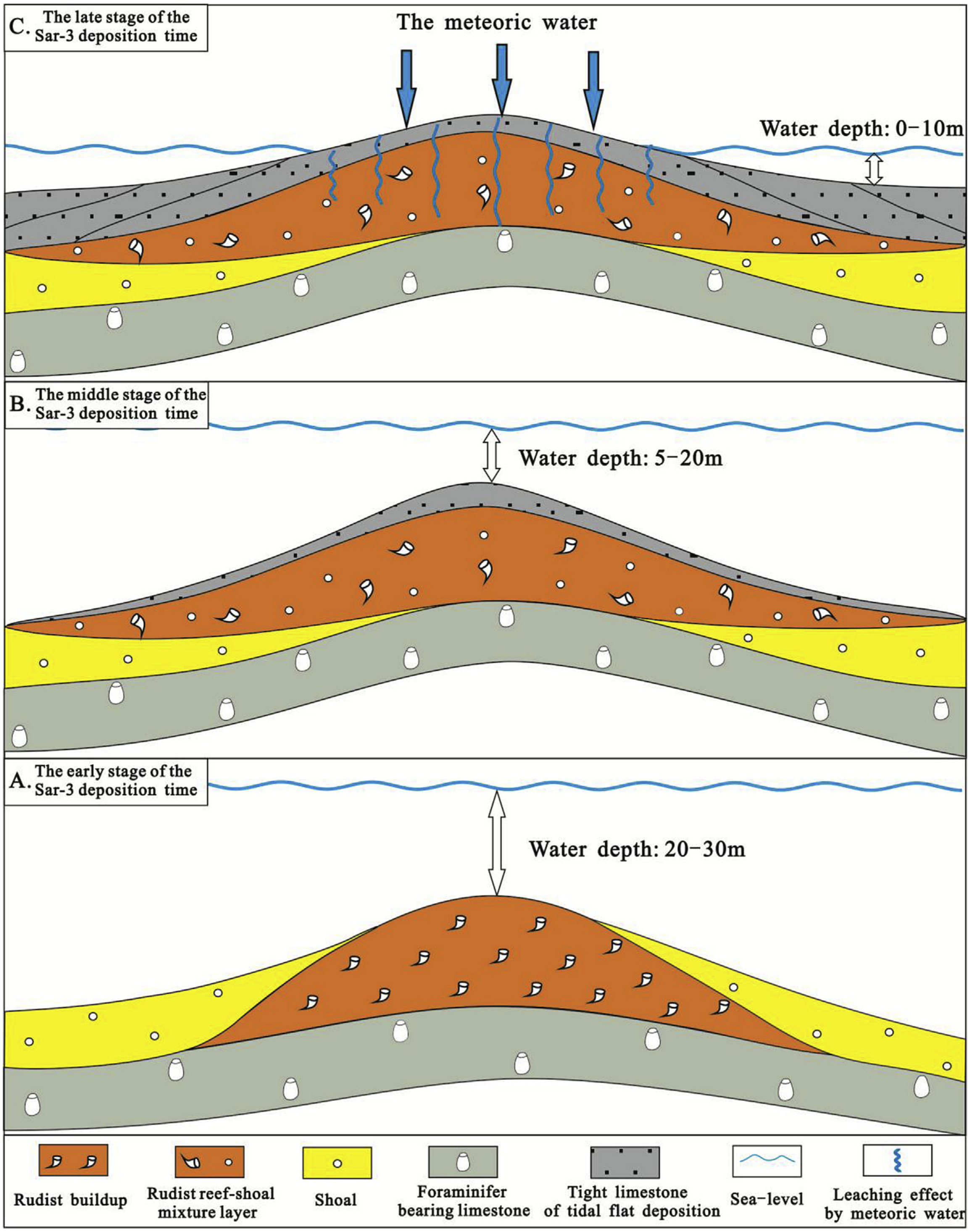

Fig. 9. Schematic diagram of the vertical reef depositional evolution pattern of Sar-3.

trend from the slope to platform (Fig. 7-B). The rudist build-ups reached the wave-base level in a short time by the uplifted dome structure and sea level fall and not into the wild-colonial stage. They were eroded and rudist fragments were dispersed over a wide area to form the reef-shoal mixture moundy bed of reef fragments, coarse intraclast and carbonate mud. In the middle-late depositional stage of Sar-3, the tidal flat environment developed by the falling sea level, the multi-stage tidal sediments deposited in the fringe area of the Paleo-high, and the stable tidal channel formed in the Paleo-high valley area (Fig. 9-B). The local subaerial exposure environment formed at the last stage of SEQ-5 such as the exposed island of the ocean. The meteoric water leaching of fresh water was the important factor influencing the reservoir property and architecture. The crest of the Paleo-high has experienced the longer exposure and received the stronger diagenesis alteration (Fig. 9-C).

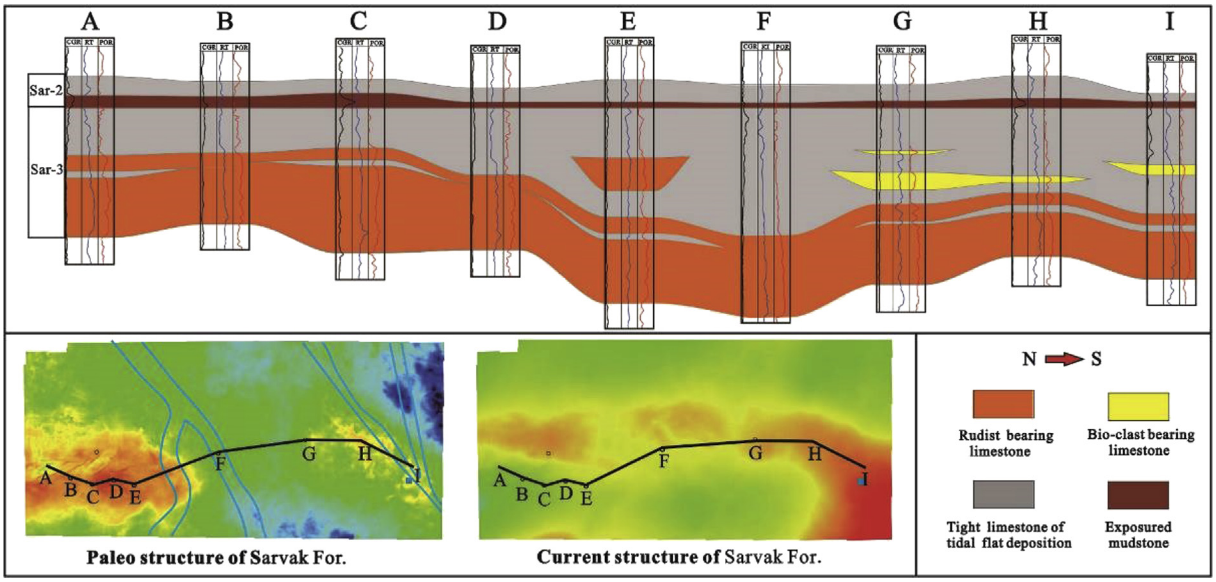

Fig. 10. Stratigraphic correlation diagram of Sar-3 (N–S).

5.4. Reservoir architecture

As the rudist organic framework could keep the primary pore like visceral foramen, and easily forming of the secondary dissolve pores of the unstable aragonite framework at the syn-diagenetic stage [6,20–22,12,10,19,28], on which the lower Sar-3 rudist bearing limestone was the prime reservoir of the field, and the upper tidal flat tight limestone was non-reservoir and played the role of the interlayer. So that, Sar-3 holds the typical dual architecture which was the lower of the rudist bearing reservoir and the upper of the dense limestone interlayer, and the thickness of both is controlled by the paleo-structure. The paleo-high has the thick reservoir and relatively thin tight limestone, and conversely in the paleo-low area. In the channel zone, as the entrenched channel was filled with fine sediments, the thickness of the tight limestone of the upper Sar-3 increased sharply to 10–20 m. The completed exploration has proved this finding as described in Fig. 10.

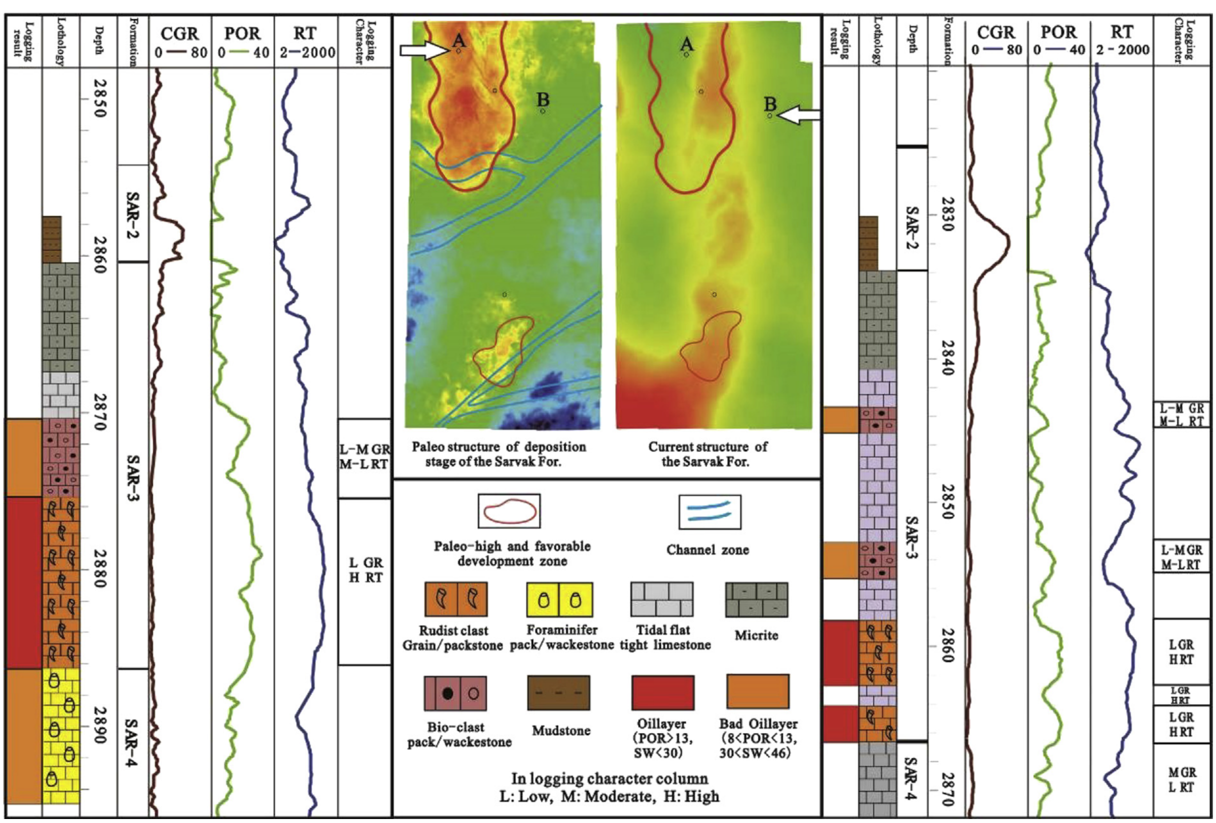

Fig. 11. Discrepancy of the vertical reservoir configuration in different position of the paleogeomorphic trap.

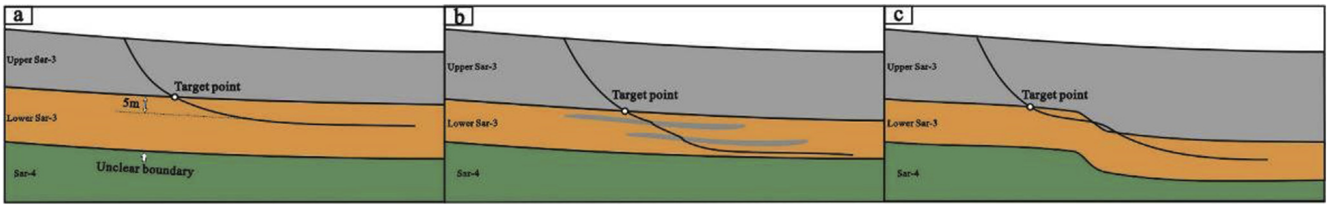

Fig. 12. Conceptual schematic diagram of the development strategy in different zones.

6. Development strategy

6.1. Paleo-high

The trap of the SA oil field evolved from the relieved anticline of the N–S trend into a long and narrow anticline bearing two crests [29]. Related to the reservoir, the main controlling factor was the depositional paleo-structure located in the paleo-high (the crest and flank area of the current northern high point). It witnesses the favorable development zone having the thick rudist-bearing reservoir with good property resulting from the strong leaching effect in the diagenesis stage (Fig. 11).

The reservoir of Paleo-high is characterized mainly as a thick and good property reservoir but the boundary of Sar-3 and Sar-4 is not distinct from the long time leaching of the subaerial exposure (Fig. 11). During the drilling process, it is difficult to distinguish the lower boundary by LWD (only GR and RT data available) and mud logging data. Therefore, it was proposed to consider a development strategy in the drilling process that involves the following approach: 1) If a good hydrocarbon show is seen with rising RT and declining GR of the LWD data, continue drilling vertically for 5 m. 2) Keep the well trajectory in the middle of reservoir along the formation slope (Fig. 12-a).

6.2. Paleo-low

The reservoir of Paleo-low is characterized mainly by the thinning reservoir thickness of 8–15 m interbedded with some thin interlayers of 1–3 m, and the upper tight limestone increasing to the 10–20 m. The key point is to control the well trajectory within the reservoir. A drilling strategy based on different logging characteristics of interbed in Sar-3 and upper Sar-4 (Fig. 11) has been proposed. It is based on the following approach: 1) Once a good hydrocarbon show is indicated with rising RT and declining GR, adjust the trajectory and cross the reservoir at a low dip angle of 88–89°. 2) If the hydrocarbon show is weaker but there is no change in GR and RT, this indicates the interlayer has been drilled and is still within the Sar-3 reservoir. Hence, increase the drilling angle and down probe, and once into the reservoir again, adjust the trajectory at a low dip angle of the 88–89°. 3) When the hydrocarbon show is weaker and the GR is rising and RT is declining, this indicates Sar-4 zone has been reached. Adjust the trajectory by rising slightly and drilling parallel to the formation dip angle. Ensure the first half of the section crosses the entire reservoir of the lower Sar-3. For the second half, keep the trajectory in the bottom of the reservoir (Fig. 12-b).

6.3. Channel zone

In the channel zone, for the target point setting it should be considered that the tight limestone thickness of the upper Sar-3 in the geological design proposal. If the horizontal section is intended to extend into the channel zone while drilling, adjust the well trajectory across the reservoir before reaching the channel zone according to the seismic interpretation, and then direct the drilling at a high dip angle as far as possible in the thickened tight limestone of the upper Sar-3 (low GR and high RT on LWD show) to cross it and rapidly reach the lower reservoir. Then keep the well trajectory in the middle of reservoir as in the paleo-high zone (Fig. 12-c).

7. Conclusion

The rudist build-up of the lower Sar-3 is situated in the Paleo-high and was formed from the Alps tectonic activity. The rudist reef reached the wave-base level in a short time by the formation uplift and not into the wild-colonial stage. It was destroyed, eroded, transferred and redeposited to form the reef-shoal mixture moundy bed. The tidal flat environment was developed by the sea level fall in the upper Sar-3 and later deposited the tight limestone of the tidal flat. The local subaerial exposure environment was formed on the top of the Sar-3. The meteoric water leaching was an important factor in influencing the reservoir property and architecture. To sum up, Sar-3 holds the typical dual architecture consisting of the rudist bearing reservoir at the top and the dense limestone interlayer below. The thickness of each is controlled by the paleo-structure. The stable tidal channel formed in the paleo-high valley area lead to the thickening of the upper Sar-3 tight limestone. Based on reservoir characteristics of different zones in the field, the following development strategy has been proposed: In the paleo-high, keep the well trajectory in the middle of the reservoir. In the paleo-low, make the well trajectory cross the reservoir in the first half of the section and keep it at the bottom of the reservoir in the remaining half. In the channel zone, drill across the abnormal thicken tight limestone rapidly and keep drilling into the middle of the reservoir.

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